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A new style solar-driven diffusion absorption refrigerator and its operating characteristics

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Abstract

In order to utilize clean energy such as solar energy to reduce electricity consumption in heating, ventilating, air conditioning and refrigerating (HVAC&R) engineering, the author developed a new style diffusion-absorption refrigerator (DAR) with solution pumps. It can be driven by low-temperature heat sources, in which $LiNO_3$-NH_3-He is used as working fluids and an adiabatic spray absorber with a plate-type solution cooler is designed to enhance the mass and heat transfer, respectively. This paper is mainly concern on the principle and operating performance of the DAR, especially the relationships of evaporator temperature (T_e), absorber temperature (T_a) and parameters such as the volume flow rate and inlet temperature of $LiNO_3$-NH_3 solution sprayed from the top of the adiabatic spray absorber. Based on measured data and theoretical analysis, the solution circulation ratio is also presented. Analyses indicate that in this DAR system, T_e mainly depends on T_a rather than condenser temperature (T_c) and generator temperature (T_g). Thus T_e and the performance of the DAR can be modulated by changing parameters of the sprayed solution. The results show that this DAR system can be driven by solar energy to meet the requirements of air conditioning, freezing or else. A typical operating experiment shows when temperatures of heat source (hot water temperature T_{ws}), T_g, T_a and T_c are 92.7℃, 87.0℃, 29.6℃ and 21.6℃, respectively, the lowest T_e is -13.0℃, the corresponding refrigeration capacity and coefficient of performance (COP) are 1.9kW and 0.156, respectively.

Keywords: solar energy; diffusion-absorption refrigerator; spray absorber; $LiNO_3$-NH_3; plate heat exchanger

1. Introduction

Diffusion absorption refrigerator (DAR) is a triple-working fluid system. In this system, the most common working fluid is $NH_3/H_2O/H_2$. In which, NH_3 is refrigerant, H_2O is absorbent and H_2 is used as diffusion gas. DAR was firstly developed by Platen and Munters in 1928 [1] and since then lots of

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researches on it have been published, such as [2-6]. DAR can be driven by low-grade thermal energy such as solar energy and waste heat sources which can reduce the electricity consumed by refrigerators and air conditioners. Thus, the growing concerns about energy and environment-sustainability in worldwide make DAR attract more and more eyes of HVAC&R engineers in recent decades. Recently, Q. Wang et al. studied a diffusion absorption refrigerator in which R23/R134a DMF and helium (He) were used as refrigerant, absorbent and diffusion gas, respectively. In their study, when the generating temperature and the ambient temperature were respectively 110-160℃ and 10-28℃, the lowest evaporating temperature could reach -40℃, but the COP was smaller than 0.07 [7]. As we know from the published references, the most of DAR systems, especially the generator is the traditional bubble pump structure. Because the solution flow rate provided by bubble pump is limited and the circulation of working fluids mainly depends on gravity which strictly restricts the relative positions of each part of DAR, it is difficult to enlarge the refrigeration capacity and maintain its small dimensions at the same time. Even adopting multi lift tubes in generator can increase the amount of circulating solution and enlarge refrigeration capacity, but the height and volume of the set are still very huge. For example, Uli Jakob and Ursula Eicker developed a solar-driven DAR named DACM in 2003, in which 19 lift tubes were adopted to circulate the solution and the refrigeration capacity was up to 2.5 kW, but the height and weight reached 2.4m and 290kg, respectively [6]. This obviously impedes the application of DAR in the fields requiring large refrigeration capacity and small area or volume occupation.

In order to enlarge refrigeration capacity and reduce the dimensions, the authors (Handong Wang et al.) developed a new style DAR driven by solar energy and natural gas, the theoretical results showed that the COP of the new DAR varied in the range of 0.11～0.5 [9, 10]. The author also carried serials experiments to investigate the characteristics and visualization of spray absorber, system performance and heat transfer characteristics of plate heat exchangers [11-14]. In these researches, low power-consumption pumps were used to transport solutions, an adiabatic spray absorber instead of traditional falling-film absorber and plate heat exchangers were used to separately enhance mass and heat transfer. It also showed that the new DAR could be driven by 60～72℃ hot water to produce 5℃ evaporator temperature; when the hot water temperature varied in the range of 83～96℃, the lowest evaporator temperature could reach -13℃, and the corresponding refrigeration capacity and COP were 1.90～4.22kW and 0.177～0.332 [14]. The attractive characteristic of low-temperature driving indicates solar energy and other low-grade thermal energy can be easily used to drive this new type DAR.

What presented here is mainly about the principle, the factors influencing evaporator temperature (T_e) and the actual solution circulation ratio, with the desire for finding out the suitable ways to improve the performance of the new type DAR.

Nomenclature

COP	Coefficient of performance
f	solution circulation ratio
p	pressure, Pa
T	temperature, ℃
Subscripts:	
a, c, e,g	absorber, condenser, evaporator and generator, respectively
s,in	inlet parameter of sprayed solution
ws	hot water source

2. The New Style DAR System and Experiment Set

The new style DAR consists of solar energy water heater, generator, vapor-solution separator, condenser, adiabatic spray evaporator and evaporator heat exchanger, adiabatic spray absorber and solution cooler, solution heat exchanger, reservoir and circulation pumps, and so on. The diagram of flow chart is shown in Fig.1. In which, the generator, condenser, evaporator heat exchanger, solution cooler and solution heat exchanger are plate heat exchangers. The working fluid is the triple fluid of $LiNO_3$-NH_3-He. In which $LiNO_3$, NH_3 and He (helium) are absorbent, refrigerant and diffusion gas, respectively. The working process of the DAR shown in Fig.1 is described as the following:

At first, the hot water produced by solar water heater is pumped into generator and heats the strong solution (high concentration of ammonia). When the temperature of strong solution reaches its saturate point, ammonia vapor escapes and separated from solution in the vapor-solution separator. Vapor is condensed by cooling water in the condenser and liquid ammonia subsequently enters the spray evaporator in which diffusion and evaporation takes place and some liquid ammonia evaporate to cool down the remained liquid ammonia. Then the remained liquid ammonia at low temperature is pumped into evaporator heat exchanger to exchange heat with the coolant and subsequently returns to evaporator to take part in the next diffusion-evaporation process. And the evaporated ammonia vapor in evaporator mixes with the diffusion gas He and then flows into the spray absorber by one of the gas pipes. At the same time, the weak solution separated from vapor-solution separator flows through solution heat exchanger and is cooled down by the strong solution leaving from reservoir. The pre-cooled weak solution is then pumped through the solution cooler and sub-cooled by cooling water, and subsequently sprayed into the spray absorber. In spray absorber, the falling weak solution absorbs ammonia vapor from the gas mixture (NH_3 and He) and becomes strong solution at the outlet of absorber, while the gas mixture with less ammonia, because of its smaller density, rises and enters evaporator by the other gas pipe to take part in the next diffusion-absorption process. The strong solution then leaves absorber and enters the reservoir, and is consequently pumped into the generator after preheated by the high temperature weak solution in the solution heat exchanger. It can be seen that there are two circulations in the operation. One is the solution circulation in the circuit consisting of generator, vapor-solution separator, solution heat exchanger, solution cooler, spray absorber and reservoir. The other is the gas circulation in the circuit mainly consisting of spray evaporator and spray absorber.

DAR has advantages such as single-pressure, no need of throttling valve, little noise, easy maintenance and long service life, and so on. The new DAR shown in Fig.1 can be driven by low-grade energy such as solar energy. The equipped low power-consumption pumps not only increase the amount of circulating solution and make it possible to enlarge refrigeration capacity, but also avoid the strict limitation of relative position of each part. Moreover, the adoption of adiabatic spray absorber and plate heat exchangers makes it more compact. It should be mentioned that the circulation pumps in this DAR are just used to overcome the flow resistance. This is different to the ones used in other absorption refrigeration systems in which the pumps should provide higher pressure to establish high pressure region. So the input power of each pump in Fig.1 is very small, which can obviously reduce electricity consumption.

In Fig.1, the solar water heater is a type of internal-concentrator solar collector equipped with a hot water tank. Measurements showed that in sunny days, temperature of hot water in the tank could reach 80～90℃ and the hot water could be directly used to drive the DAR. But the supplementary electrical water heater should operate when solar energy was not enough, such as in cloudy or rainy weather.

During experimental operating, the cooling water between the solution cooler and condenser can be conveniently changed from series connection to parallel connection, and the flow rate can also be modulated by valves in the cooling water pipes.

A LabVIEW data acquisition system (DAQ) is set to measure the pressure, flow rates and temperatures of the DAR. In which, the pressure is measured by a sputtered film sensor with precision of ±0.1%. The temperature sensors are T-type thermo-couples calibrated by a Pt-100 sensor in the range of -20～96℃ and the flow meters are intelligent electromagnetic flow meters with precision of ±1.0% (for water measurement) and turbine flow meters with precision of ±0.5% (for solution measurement).

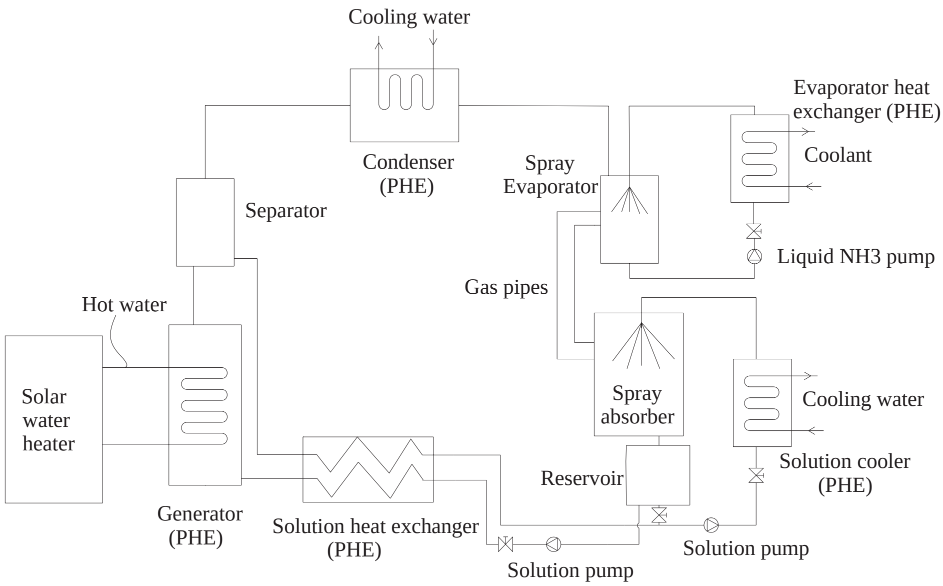


Fig. 1. Diagram of flow chart of the new type DAR (PHE means plate heat exchanger)

3. Operation measurement and Analysis

Researches have shown that the new style DAR could be driven by low-temperature heat source. It also indicated that the evaporator temperature (T_e) varied with the temperatures of absorber (T_a), generator (T_g) and condenser (T_c). This paper mainly focuses on analyzing the possible factors influencing the value of *Te* and tries to find out the key factors.

In the DAR system, because of the circulation of gas mixture (mixture of NH_3 and He) existed between absorber and evaporator, the absorbing and evaporating processes will affect each other so that T_a and T_e will affect each other. In the adiabatic spray absorber, after absorbing ammonia vapor, the sprayed solution temperature will rise and at last reaches to the equilibrium temperature which matches to the saturated temperature of outlet solution. Thus, T_a mainly depends on the initial parameters of sprayed solution and the level of absorbing process. The initial parameters of the sprayed solution include inlet temperature, flow rate and inlet concentration of sprayed solution, etc. The level of absorbing process depends on the mass fractions of ammonia in the inlet and outlet gas mixture, the droplet size of sprayed solution, the contact area and time of sprayed solution and gas mixture. This paper mainly investigates the influence of the initial parameters. The influence of T_a, T_g and T_c on T_e are also discussed in details.

3.1. Relationships of T_e, T_a, T_g and T_c

Figs.[2-4] show the different effect of T_a, T_g and T_c on T_e, respectively.

Fig.2 shows when temperatures of heat source (hot water temperature T_{ws}), T_g and T_a are the value of 89.1℃, 84℃and 35.5℃, respectively, as T_c in Fig.2(a) is 5.8℃ lower than that in Fig.2(b), T_e in Fig.2(a) is 1.0℃ lower than that in Fig.2(b). This illustrates that the influence of T_c on T_e is not very obvious. Experiments show that in some conditions, T_e may be lower at a higher T_c (as shown in Fig.6). From this point, it can be pronounced that T_c is not the direct factor affecting the value of T_e.

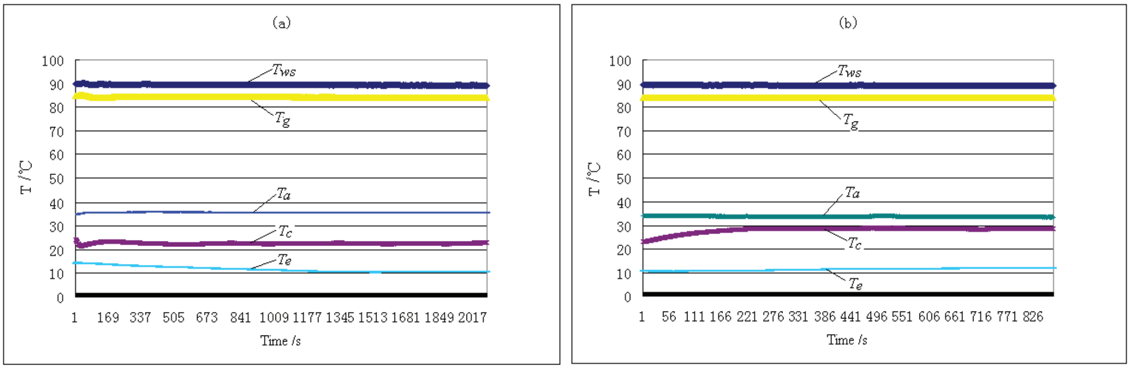
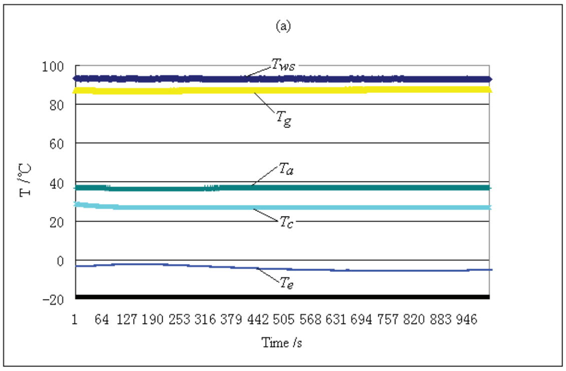


Fig. 2. Influence of different T_c on T_e (T_{ws} stands for hot water temperature). (a) Lower T_c; (b) Higher T_c

In Fig.3, when temperatures of heat source (T_{ws}) and T_g are the same value of 93.1℃ and 87.4℃, respectively, and T_c varies in the range of 27～27.4℃, if T_a decreases 1℃, the lowest T_e will decrease 1.5℃. The influence of T_a on T_e is obvious. Other experiment results also demonstrate the same effect. In other words, T_e increases obviously with increase of T_a. This indicates that T_a is one of the main factors directly influencing T_e.

Fig.4 shows the results at different T_g. In general, it may be thought that the higher the T_g is, the lower the weak solution concentration will be, thus the lower T_e will be obtained. But by comparing Fig.4(a) and (b), it can be found that though T_g in Fig.4(b) is lower, the lowest T_e in Fig.4(b) is 13℃ lower than T_e in Fig.4(a). It means that even T_g is higher, T_e may be higher too.

This is mainly caused by the lower T_a and T_c in Fig.4(b), both of which are about 10℃ lower than that in Fig.4(a). It can be seen that the inlet temperature of sprayed solution ($T_{s,in}$) in Fig.4(a) is almost 10℃ higher than that in Fig.4(b), which subsequently causes higher T_a and T_c in Fig.4(a). When T_c is higher, the pressure of the DAR system is higher, too. The system pressure curves are shown in Fig.4(c) and (d), respectively. As saturate temperature of the strong solution in generator increases with pressure increasing, higher pressure requires higher heat source temperature to generate the strong solution. In other words, though T_g in Fig.4(a) is higher, because of the corresponding higher system pressure, the concentration of weak solution leaving generator/separator is even higher so that its absorbing ability is poorer which of cause results in a higher T_e. This indicates that T_e not always decreases with increase of T_g, and T_g is not the dominant factor influencing T_e. Furthermore, it demonstrates on the other hand that T_e closely depends on T_a.



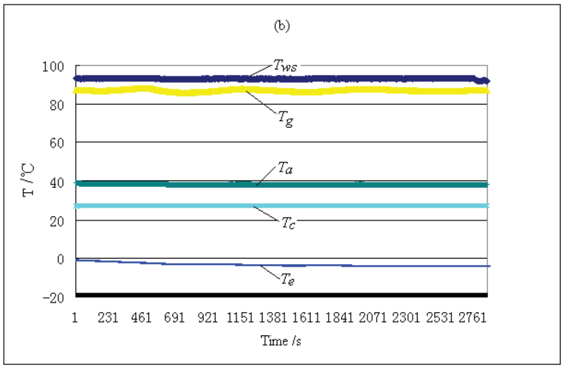


Fig. 3. Influence of different T_a on T_e. (a) Lower T_a; (b) Higher T_a

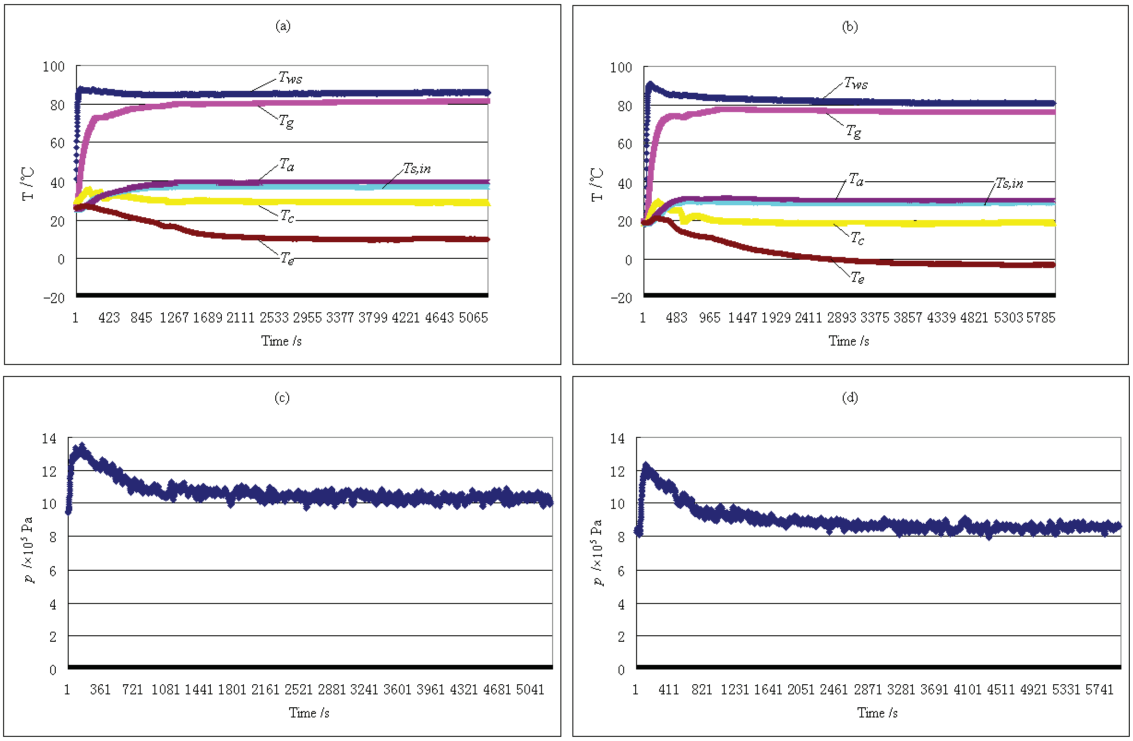


Fig. 4. Influence of different T_g on T_e ($T_{s,in}$ stands for inlet temperature of sprayed solution). (a) Higher T_g; (b) Lower T_g; (c) Pressure at higher T_g; (d) Pressure at lower T_g

Based on above analysis, it can be declared that in this new style DAR, T_e is mainly determined by T_a. T_c mainly influences the system pressure and indirectly affects the lowest T_g. Both T_c and T_g do not directly and obviously affect T_e.

3.2. Influence of sprayed solution

When the inlet concentrations of sprayed solution are different, curves of temperatures are shown in Fig.5. It can be found that compared to the curves at high concentration condition, T_g at low concentration condition is 2℃ higher, but T_c and T_a are 3.4℃ and 2℃ lower, respectively, while the T_e at low concentration condition is 1.6℃ lower. It means that T_e decreases with concentration decreasing. But theoretical analysis indicates that if the other conditions are the same, the solution with lower concentration should have strong absorbing ability so that T_a should be higher, too. Why is the measured T_a lower at low concentration? It can be explained from two effects. The first one is the inlet temperature of sprayed solution ($T_{s,in}$) is lower at low concentration condition, which causes lower T_a. The other is that the flow rate of sprayed solution at low concentration is slightly smaller than that at high concentration condition so that the absorbing capacity of the solution caused by flow rate is slightly smaller and it will slightly decrease T_a. But the importance and the influence level of flow rate need further study in the future.

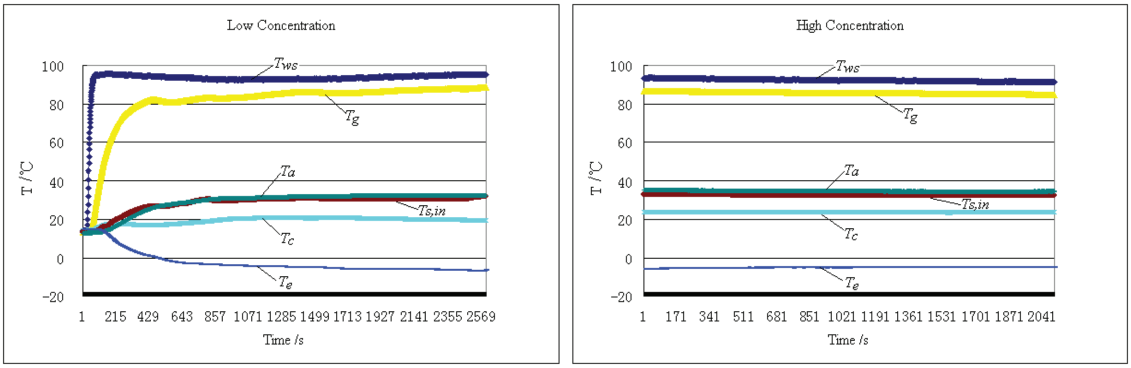


Fig. 5. Influence of sprayed solution concentration ($T_{s,in}$ stands for inlet temperature of sprayed solution)

When the concentration of sprayed solution is the same but the inlet temperature ($T_{s,in}$) is different, the corresponding temperature curves are shown in Fig.6. It shows that at given concentration, the lower the $T_{s,in}$ is, the T_a and T_e are lower, too, even though T_c is 2.6℃ higher. The fluctuation of T_c in Fig.6(a) may be caused by the abnormal gas transportation in the balance pipe which connects absorber and outlet of condenser. During operation at low concentration condition, it is found that periodical refrigerating phenomenon appears and last for nearly 1200 seconds at the connection point of balance pipe and liquid ammonia pipe, and the more details need to be investigated in the future.

Experiments on the influence of sprayed solution flow rate are also carried out by keeping the inlet concentration and temperature at constant values. The results show that T_a increases slightly with increase of sprayed solution flow rate, but T_e almost maintains constant. It indicates that increasing the amount of sprayed solution can slightly improve the absorbing ability of absorber, but it doesn't obviously affect T_e. The reason may be explained as the following: on one hand, by increasing the flow rate of sprayed solution, the absorbing ability of spray absorber increases and more ammonia vapor is absorbed from the gas mixture in absorber; when the gas mixture with less ammonia vapor leaves absorber and enters evaporator, the pressure difference of ammonia between gas phase and liquid phase in evaporator also increases, i.e. it enlarges the diffusion motive power and enhances the diffusion-evaporation process in evaporator, so that it will slightly decrease T_e. On the other hand, enhancement of absorbing and evaporating process accelerates the gas mixture circulation and more gas mixture with higher temperature (T_a) enters evaporator so that it will increase the evaporator temperature (T_e). These two different effects may be the reason why T_e maintains constant at this condition.

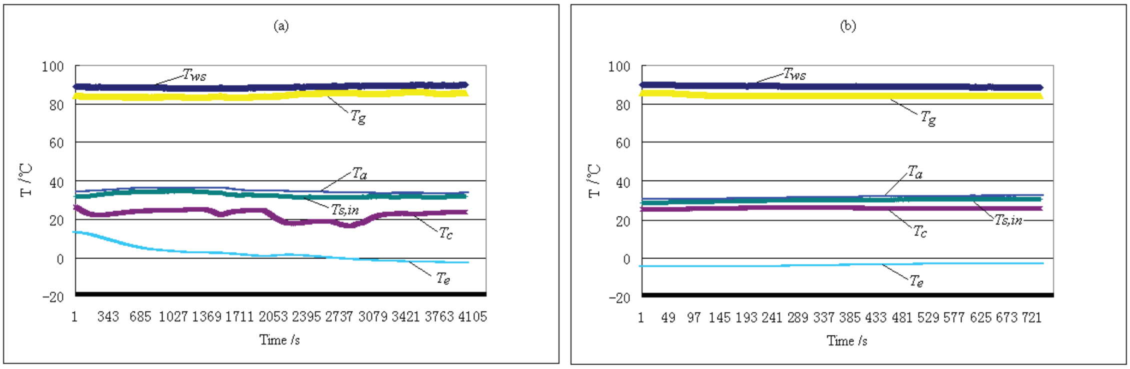


Fig. 6. Influence of inlet temperature of sprayed solution ($T_{s,in}$). (a) Higher inlet temperature $T_{s,in}$; (b) Lower inlet temperature $T_{s,in}$

3.3. Typical performance and solution circulation ratio

The new style DAR can produce different evaporator temperature (T_e) and T_e may be easily modulated by changing T_a to meet the requirements of air conditioning or freezing. When it is used for freezing, T_e should be below -10℃. Can it still be driven by solar energy with low evaporator temperature? As an example, a typical operation with low T_e gives the answer. One of experiments showed when temperatures of heat source (T_{ws}), T_g, T_a and T_c were 92.7℃, 87.0℃, 29.6℃ and 21.6℃, respectively, the lowest T_e reached -13.0℃ (average T_e was -11.2℃), the corresponding refrigeration capacity and COP were 1.9kW and 0.156, respectively. In this paper, COP is defined as COP=Q_e/Q_g, in which Q_e and Q_g are refrigeration capacity and heat input of generator, respectively. It can be found that this new DAR is a satisfactory candidate for utilizing solar energy in the fields of HVAC&R engineering. At above working condition, based on the measured data and theoretical calculation, the corresponding solution circulation ratio (f) is also calculated and presented in Fig.7.

During the operation, as the solution flow rate is modulated by the solution surface level in vapor-solution separator, f varies in a certain range. The measured average f is 12.38 which is very close to the value of generally used LiBr-H_2O absorption refrigerator ($f \approx 11$). The f value sounds reasonable when the lower T_e of this new DAR is taken into account.

Based on the above analysis, if COP is desired to be higher by reducing solution circulation ratio f, the best way is to decrease T_c and the system pressure to efficiently decrease the required lowest T_g. It will be more helpful to utilize solar energy to drive the new DAR.

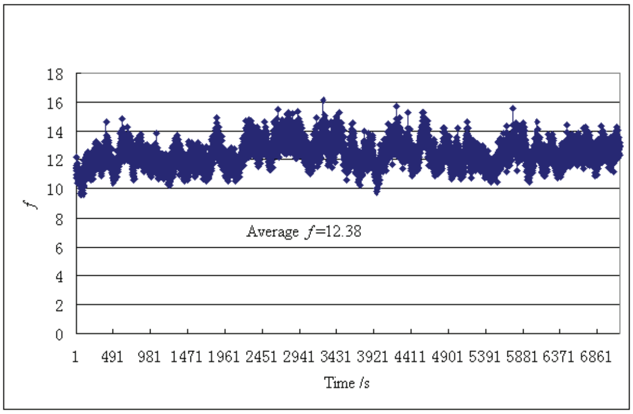


Fig. 7. Typical solution circulation ratio f (T_e=-13℃)

4. Conclusion

Based on the experiments and analysis, it can be concluded as the followings:

- 1) When the DAR operates at the condition in which the temperatures of heat source (T_{ws}), generator (T_g), absorber (T_a) and condenser (T_c) are 92.7℃, 87.0℃, 29.6℃ and 21.6℃, respectively, the lowest T_e reaches -13℃, the corresponding refrigeration capacity and COP are 1.9kW and 0.156, respectively. The average solution circulation ratio f is 12.38. The advice on best way to improve COP by reducing f is to decrease T_c and T_a so that it is helpful to utilize low-temperature heat source. This DAR can be driven by solar energy to meet the requirements of air conditioning and freezing. It is helpful to stimulate the application of renewable and clean solar energy in HVAC&R engineering.
- 2) In the new style DAR, the main factor affecting T_e is T_a, and T_e increases with T_a increasing. Thus T_e can be changed by modulating T_a to meet different requirements of refrigerating temperature (e.g. air conditioning and freezing, etc.).
- 3) T_g and T_c do not directly determine T_e. But T_c is related to the system pressure. The lower T_c is, the lower the system pressure is, too, so the required lowest T_g is also lower. Therefore, lower T_c is helpful to utilize low-temperature heat source such as general solar energy water heater.
- 4) When the inlet temperature and concentration of sprayed solution in the spray absorber are lower, T_e will be lower, too. Decreasing the inlet temperature and concentration of sprayed solution is also helpful to improve absorbing efficiency. When the concentration of sprayed solution is given, increasing the flow rate of sprayed solution can improve absorbing efficiency in certain degree but doesn't obviously affect T_e.
- 5) Based on 2) and 4), it can be found that in this new style DAR, T_e can be adjusted by changing the values of T_a, $T_{s,in}$ and inlet concentration of the sprayed solution in spray absorber. Because T_a varies with $T_{s,in}$, while $T_{s,in}$ depends on the temperature and flow rate of cooling water flowing through the solution cooler, thus T_e can be conveniently adjusted by changing parameters of cooling water.

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